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PROJECT WISH: THE EMERALD CITY

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THE OHIO STATE UNIVERSITY

INTRODUCTION

Project WISH (Wandering Interplanetary Space Harbor) is a three-year design effort currently being conducted at The Ohio State University. Its goal is the design of a space oasis to be used in the exploration of the solar system during the mid-twenty-first century. This spacecraft, named Emerald City, is to conduct and provide support for missions to other planetary bodies with the purpose of exploration, scientific study, and colonization. It is to sustain a crew of between 500 and 1000 people at a time, and be capable of traveling from a nominal orbit to the planets in reasonably short flight times. Such a ship obviously presents many technical and design challenges, some of which have been examined through the course of Project WISH.

This year, Phase II (1990-1991) of Project WISH was carried out. The basic design of the Emerald City resulting from Phase I (1989-1990) was taken and improved upon through more detailed analysis and revision. At the core of this year's study were orbital mechanics, propulsion, attitude control, and human factors. Throughout the year, these areas were examined and information was compiled on their technologies, performances, and relationships. Then, using the data obtained through these studies, two specific missions were designed: an envelope mission from a nominal orbit of 4 AU to Saturn and a single-point design for a specific mission from the Earth to Mars. The latter was designed in view of the special interest that Mars is attracting for near-future space exploration. The mission to Saturn has all the first six planets within its flight envelope in less than or equal to a 3-year flight time at any time upon demand, and it has Uranus in its flight envelope most of the time upon demand. These mission studies provided data on the approximate size, weight, number of engines, and other important design values that would be required for the Emerald City.

ORBITAL MECHANICS

Consideration of orbital mechanics dealt primarily with finding the ΔVs for transfers from a nominal orbit to a target planet in a given time. The original design requirement was for the Emerald City to be able to go from a nominal orbit to any planet in the solar system in three years or less. However, this requirement was modified in order to reduce the ΔVs required so as to give the project a more workable design problem. First, the planets were categorized according to their envisioned role in manned space exploration during the mid-twenty-first century. The ability of the Emerald City to make transfers to a planet was then based on what category the planet fell into. The first category includes Earth, Mars, and Jupiter, planets that were felt to be very important. The design goal for the first category was to be able to make a transfer to one of these planets 100% of the time on demand in three years or less. In the second category of planets were those deemed important, namely Venus, Saturn, and Uranus. The design goal for this category was to be able to make transfers to these planets most of the time in flight times of up to five years. The final category consists of planets deemed to be unimportant for Project WISH and is made up of Mercury, Neptune, and Pluto. It is envisioned that there would be little need for a ship such as the Emerald City to make transfers to these planets, and thus any capabilities to reach them would be an added bonus.

Once these new requirements were identified, the ΔVs needed to make transfers to the planets were examined. This was done by using a high-impulse orbital mechanics computer code and the concept of the synodic period, which is the time it takes for a certain orientation to recur between two orbiting bodies. The synodic period is important because the ΔVs will essentially repeat cyclically with a period given by the synodic period. The ΔVs required for all the planets were found over one sample synodic period for a range of nominal orbit radii and flight times. These results were then analyzed by finding the percentage of the synodic period that a transfer could be made under a certain ΔV level. These percentages were used to compare the ability of the Emerald City to reach the different planets from various nominal orbits. Based on the results from this analysis, a circular nominal orbit of 4 AU was selected, which met or exceeded all the design requirements mentioned earlier for a round trip ΔV of 50 km/s. This value for ΔV was then given to the propulsion group for their system analysis.

Another problem examined by orbital mechanics was ΔV minimization. In this study, the effects of finite thrust levels were incorporated along with the equations for a free-flight orbit. From these equations, an optimization problem was formulated, with an objective function given by the total ΔV. The constraints were based upon the limits of initial acceleration, total flight time, burn times, and a rendezvous condition that insures that the Emerald City and the target planet meet. Although the problem was set up and all the functional relationships were determined, the computer coding of the problem into an optimization routine is left for next year (1991-1992), Phase III of Project WISH.

PROPULSION

The propulsion system of the Emerald City was the subject of much work during Phase II of Project WISH. The first step in the analysis of the propulsion system was the examination of the equations relating to the propulsion parameters such as the thrust, exit velocity, specific impulse, burn times, etc. By graphing these equations, relationships were noted and an estimate of the order of magnitude of these parameters was obtained. It was observed that for a ship such as the Emerald City, with very large mass expected and high ΔV requirements, a propulsion system capable of providing enormous amounts of impulse at high specific impulse and thrust levels would be needed. It was felt that, of the potential propulsion systems in the twenty-first century, the gas-core nuclear rocket offered the most promise as the propulsion system for the Emerald City.

The gas-core nuclear rocket consists of five different components: the pressure shell, the moderator, the turbo pump, the nozzle, and the radiator. It uses the thermal energy generated by the fissioning fuel, U^{233}, which is in a gaseous state at very high temperatures. The turbopump pumps liquid hydrogen around the circumference of the pressure shell to aid in the cooling process of the moderator. Next, the liquid hydrogen is pumped into the cavity where the gaseous U^{233} is located and the fission process is occurring. At this time, the hydrogen is heated to very high temperatures and expelled through the nozzle to produce thrust. The moderator is present to block and reflect neutrons, which allow the fission chain reaction to be maintained.

The gas-core nuclear rocket was selected because of the relatively high values for thrust, F, and specific impulse, I_{sp}. These parameters, along with values for the cavity diameter and the ratio of the U^{233} volume to the cavity volume were estimated in order to calculate the propulsion system component masses. A computer program was written to find these masses as well as the mass flow rates of the uranium and hydrogen. This program also calculated temperatures as well as other engine parameters in the cavity, at the throat, and at the exit.

Next, the number of engines that would be required for a mission was found. This figure is given by the formula

$$n = \frac{m_{dry}\, I_{sp}\, g}{F_i\, t_{pr}} \left(e^{\frac{\Delta V}{I_{sp}\, g}} - 1\right) \qquad (1)$$

where m_{dry} is the dry mass of the Emerald City, F_i is the thrust of one engine, t_{pr} is the burn time, and ΔV is the change in velocity that is required for the given mission. Once the number of engines is found, the total mass of the propulsion system and hence the payload mass can found.

HUMAN FACTORS

To provide life support for 500-1000 people on a ship with an expected lifetime of at least 50 years, a system was needed that required little or no resupply. Because of the magnitude of Project WISH, even a system that could be 99% efficient will waste thousands of kilograms of water a year. This fact virtually eliminates using mechanical systems for life support for the Emerald City. Attention therefore turned to organic-based methods for providing life support, such as biosphere technology, which could provide a life support system that would be 100% efficient. Biospherics is a rising science that studies the way the Earth naturally recycles all food, water, and waste. Using information from the Biosphere II project in Arizona, volume and mass requirements for the crew section of the Emerald City were estimated. These results were then used as constraints for the design of the crew section.

Another problem in the area of human factors was the need for artificial gravity. Previous experience in space has shown that without gravity bones immediately begin to decalcify and muscles weaken and atrophy. Effects of long-term exposure to zero-*g* are not completely understood, but research appears to indicate further deterioration that would reduce the possibility of returning to life in a 1-*g* environment. The crew section was therefore designed to be a torus rotating about a central pole to provide some level of artificial gravity. The relationship between spin rate (ω), gravity level (n_g), and distance from the rotating axis (r) is found to be

$$r = \left(\frac{30}{\pi}\right)^2 \frac{n_g\, g}{\omega^2} \qquad (2)$$

Possible sizes of the torus were found using this equation and the constraints on the three variables. One rpm is the upper limit for spin rate because of attitude control power requirements and the limits of human endurance. A maximum gravity level of 0.8 was used to size the torus because it was felt that this would limit the ill effects of extended weightlessness while reducing the structural mass that would be required for the larger torus radius at 1 *g*.

The final issue examined this year was radiation. Guidelines for exposure were determined from recommendations of the National Council on Radiation Protection and Measurements. The 5 rem/year limit was based on a 3% increased risk of getting cancer. The major radiation sources for the Emerald City are from the power and propulsion systems, solar flares, and cosmic radiation. Of these, cosmic radiation is of the most concern because the crew is constantly exposed to it, and the only way to protect against it is to shield the entire crew section. Of the most common materials in space applications, liquid hydrogen is the most effective shield because it does not contain neutrons that can be scattered by incident radiation. A 14-m layer of liquid hydrogen attenuates the dose from cosmic rays to just below the 5 rem/year limit. Dose rates from the exhaust of the engines and solar flares are high, but only last from 1 to 2 weeks. Specifically, the radiation from the engine plume was computed for the propulsion system parameters. When these sources of radiation are present, protection can be obtained by moving the crew to areas with extra shielding, thus keeping down the mass of the Emerald City.

ATTITUDE CONTROL

The vehicle dynamics of the Emerald City were studied during Phase I (1989-1990) of Project WISH. The attitude-stable configurations of the spacecraft (assumed to be rigid body, although this assumption will be revised next year) were determined from this study. Phase II placed more emphasis on the attitude control aspect of the problem. A study was conducted to determine the state response due to specified initial disturbances and the attitude control design requirements needed to damp out these disturbances.

The first step in the study was to determine a thruster configuration that would be used for attitude control. This configuration consisted of four clusters yielding independent control couples about the centroidal principal moments of inertia axes parallel to the torus plane. Next, the control torques on the spacecraft were calculated using this cluster configuration. This thruster configuration matrix was then substituted into the gyroscopic state equations of a spinning body, which were obtained during Phase I of the project. The control software package MATLAB was then used to design linear quadratic regulator (LQR) controls. The root-mean-square power, P_{rms}, required to damp out the disturbances, was then calculated by using the equation

$$P_{rms} = \frac{V_{ex} I_x n^2}{2D_t} \left(\frac{S^*}{\tau_c} \right)^{1/2} \quad (3)$$

where V_{ex}, I_x, n, and D_t are the thruster jets' exhaust velocity, mass moment of inertia about the x axis, and the diameter of the living quarters (torus) of the spaceship. The parameters S^* and τ_c are nondimensional control power and control time, respectively, obtained via the particular state feedback control design and the initial disturbances. The attitude power requirement was the influencing factor in keeping the spin rate below 1 rpm. The next step was the calculation of the propellant mass required for the attitude control systems and the calculation of the thrust requirements at each cluster location by studying the control input profiles. The results of this study are shown in Table 2 for the particular missions discussed earlier.

REPRESENTATIVE MISSION DESIGNS

Once the individual disciplines of Project WISH had been studied in detail, an attempt was made to produce a representative design for the Emerald City. Since the idea of Project WISH is for the Emerald City to handle a wide variety of missions, two contrasting cases were considered to find the range of the design parameters. The first one is the Saturn envelope mission with a three-year flight time and a round trip ΔV of 50 km/s, which is near the upper bound of ΔV set for the propulsion system. The second mission is a single-point design that depicts a transfer from about 1 AU outside the sphere of influence of the Earth to Mars with a ΔV of 12.6 km/s and a flight time of 1.54 yr. This would be a more common mission that the Emerald City might be required to undertake, carrying new colonists and supplies that had been shuttled to the Emerald City just outside the Earth's sphere of influence, supplying the martian colonies with materials from Earth. It was felt that analyzing these two missions would yield good estimates of the bounds for the size, mass, and configuration of the Emerald City.

The missions described above were analyzed using a methodology based on considerations discussed in the previous sections. Human factors were used to set volume and mass requirements for the torus, which was based on the crew size selection. These were based on data from the Biosphere II project and estimates for the structural and shielding masses needed. Then, a dry mass of the spacecraft was estimated and the propulsion system parameters (number of engines, propellant required, burn time, total engine mass) were found from orbital mechanics and propulsion considerations. The mass of the torus section, the propellant, and the engines were subtracted from the dry mass to obtain the payload mass. This payload mass represents cargo as well as other subsystems that have not been considered yet (power, heat rejection, attitude control thrusters, tankage, etc.). The center pole was sized to store fuel and propellant and the center of mass of the ship was found. Mass moments of inertia were then calculated and these values were used in the study of the attitude control system.

The results from the design studies can be found in Tables 1 and 2. Table 1 lists the mission requirements for the two missions and then the different masses and ship sizes. Table 2 uses the values found for these missions and finds the attitude control requirements for a given gyroscopic initial disturbance. Figure 1 shows how some of the variables listed in these tables are defined.

TABLE 1. Emerald City Design Parameters

	Saturn Envelope Mission	Earth to Mars
Crew	1000	500
ΔV_{total} (km/s)	50	12.6
ΔV_1 (km/s)	-	5.1
ΔV_2 (km/s)	-	7.5
$t_{pr,total}$ (days)	20	11.53
$t_{pr,1}$ (days)	-	5
$t_{pr,2}$ (days)	-	6.53
F_i, thrust/engine (N)	4.44×10^5	4.44×10^5
I_{sp}, specific impulse (sec)	5000	5000
number of engines	172	33
m_o (total, kg)	4.16×10^9	1.295×10^9
m_p (propellant, kg)	2.658×10^9	2.947×10^8
m_{dry} (dry, kg)	1.5×10^9	1×10^9
m_l (payload, kg)	3.457×10^8	2.165×10^8
m_w (engine, kg)	4.4376×10^7	8.514×10^6
m_{torus} (torus, kg)	1.111×10^9	7.746×10^8
m_l / m_o	0.083	0.167
m_p / m_o	0.639	0.228
V_{LH2} (m^3)	3.742×10^7	4.151×10^6
r_{pole} (m)	100	50
h_w (m)	20	20
h_p (m)	1200	528
h_c (m)	50	21
R (m)	700	700
r (m)	37	26
$z_{centroid}$ (m)	432	69
I_z (kg m^2)	5.6144×10^{14}	3.8061×10^{14}
I_x, I_y (kg m^2)	9.9568×10^{14}	2.1731×10^{14}
max/min g-levels	0.8/0.72	0.8/0.74
ω (spin rate, rpm)	0.99	0.99
r_x (m) / r_z (m)	489/367	410/542

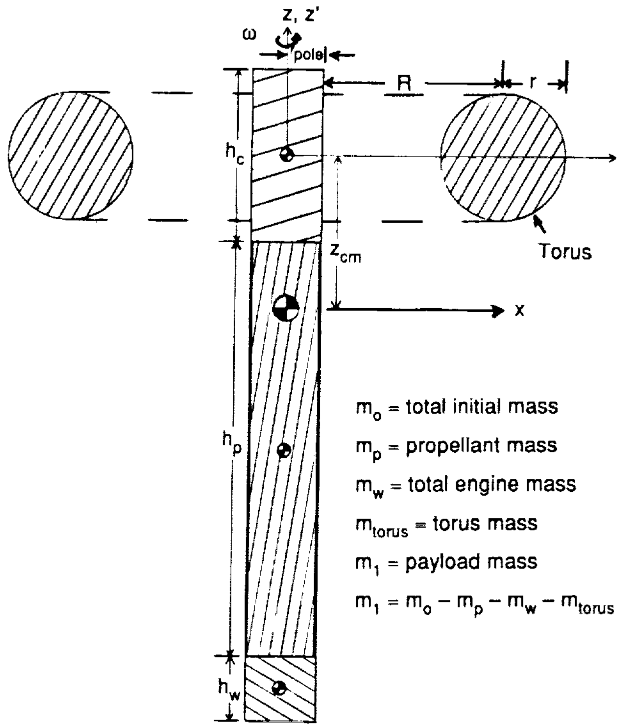

Fig. 1. Definition of design parameters.

TABLE 2. A representative attitutde control system design (Θs are rotations about the respective body axes).

I_z/I_x	0.56	1.75
Initial Disturbance	$[\Theta_x, \Theta_y, \dot{\Theta}_x, \dot{\Theta}_y] = [.1\ .1\ .1n\ .1n]$	
P_{rms} (W)	6.176×10^{12}	7.86×10^{11}
$m_{p,control}$ (kg)	2.105×10^{7}	3.458×10^{6}
$F_{control,max}$ (N)	2.988×10^{9}	1.911×10^{9}
$t_{control}$ (sec)	~ 100	~ 100